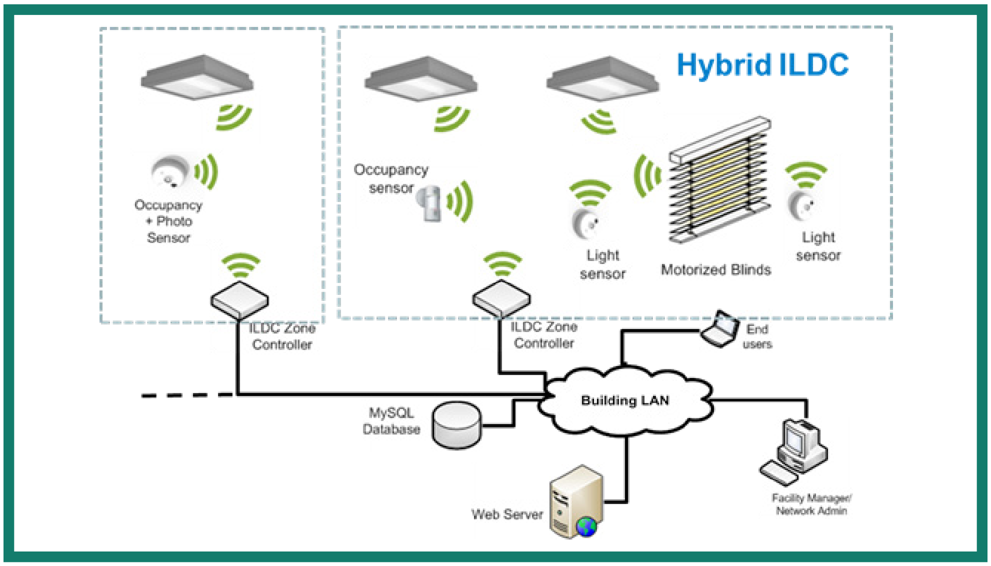
ESTCP
Cost and Performance Report

(EW-201012)



Advanced Lighting Controls for Reducing Energy Use and Cost in DoD Installations

May 2013

ENVIRONMENTAL SECURITY
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ACRONYMS AND ABBREVIATIONS

AC	alternate current
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BLCC	building life-cycle cost
BLCC5	Building Life-Cycle Cost Program
BMS	Building Management System
CO_2	carbon dioxide
COP	Coefficient of Performance
DIACAP	DoD Information Assurance Certification and Accreditation Process
DoD	Department of Defense
DOE	Department of Energy
DPW	Directorate of Public Works
ECIP	Energy Conservation Investment Program
EIA	U.S. Energy Efficiency Administration
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
EUI	energy use intensity
FEMP	Federal Energy Management Program
GHG	Green House Gas
HVAC	heating, ventilation and air conditioning
IESNA	Illuminating Engineering Society of North America
ILDC	Integrated Lighting and Daylight Control
IP	Internet Protocol
kW	kilowatt
kWhr	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LPD	lighting power density
MCF	mil cubic feet
MILCON	Military Construction
MMT	million metric tons
NIST	National Institute of Standards and Technologies

ACRONYMS AND ABBREVIATIONS (continued)

OEMS	original equipment manufacturer
PC	Personal Computer
RF	Radio Frequency
SCE	Southern California Edison
SIOH	supervision, inspection and overhead
SIR	savings to investment ratio
TOU	Time of Use
UFC	Unified Facilities Criteria
UPS	Uninterruptible Power Supply
VAR	value-added reseller
W	Watts
WECC	Western Electric Coordinating Council

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EXECUTIVE SUMMARY

BACKGROUND AND INTENT

The massive footprint of mostly old building stock in the Department of Defense's (DoD) inventory offers significant opportunities for reducing energy consumption, carbon emissions, and operating costs. Existing lighting systems in many DoD facilities consume excessive electrical energy because they are often outdated, inefficient, and lack automated controls. These factors result in increased energy consumption, higher operational, maintenance, lifecycle costs, and reduced workforce productivity. Therefore, the intent of this project is to retrofit buildings with advanced lighting control systems that combine dimmable light sources, occupancy and daylight sensors, and intelligent controls to significantly lower the lighting energy consumption as well as reduce cooling loads due to the thermal effects of lighting. Furthermore, appropriate control and monitoring systems can lower maintenance cost and improve occupant satisfaction.

LIGHTING CONTROL SYSTEMS DEPLOYED

The DoD's Environmental Security Technology Certification Program (ESTCP) commissioned a team consisting of Philips and Lawrence Berkeley National Laboratory (LBNL) to study the performance of advanced lighting control systems in DoD buildings. Philips developed and deployed the lighting control systems and LBNL carried out the evaluation of energy savings and occupant surveys by collecting pre- and post- retrofit data and performing all the data analysis. In this report, the cost and performance analysis of three lighting control systems deployed in three buildings in Ft. Irwin, California will be described below.

I. OccuSwitch Wireless is a room-based lighting control system employing dimmable light sources, occupancy and daylight sensors, wireless interconnection and modular control to provide energy savings through occupancy sensing, dimming and daylight harvesting.

II. Dynalite is a distributed control-based, wired networked building-wide lighting control system offering scene settings, personalized dimming, scheduling, occupancy sensing and daylight harvesting to provide energy savings as well as ambience for different activities.

III. Hybrid Integrated Lighting and Daylight Control (ILDC) is a combination of wireless and wired control solution for building-wide networked system that maximizes the use of daylight while improving visual comfort through an integrated control of electric lights and motorized blinds.

PERFORMANCE RESULTS

The goal of this project was to study the energy, environmental, economic and user benefits of the above three lighting control systems in DoD buildings. The performance of the three systems against the objectives and success criteria agreed upon with ESTCP are summarized in Table 1. As shown in the table, most of the objectives were met during the demonstration, with exception of two that are discussed below.

The three systems performed differently with respect to energy savings as expressed in energy use intensity (EUI)/carbon footprint reduction, peak lighting power density, and cost effectiveness. This is partly due to the differences in the characteristics of the buildings they were deployed in and partly due the energy savings features of the systems. For instance, the size of the buildings is an important parameter that determines the system cost per unit area as fixed hardware cost, such as servers and controllers are amortized over the entire area. To provide a more generalized picture that can be applied across the entire DoD facilities, three different building size scenarios have been considered—small, medium and large—defined specifically in section 7.4. With this classification, it is seen that payback <7 years is met in most cases with the exception of the small area category for the Dynalite system. The savings to investment ratio (SIR) objective (>2) is met in the large buildings for all three systems and medium buildings for Hybrid ILDC and OccuSwitch systems. In small buildings, the SIR objective is not met.

Table 1. Performance results.

Performance Objective	Success Criteria	Results								
		Hybrid ILDC			OccuSwitch			Dynalite		
Reduce electrical energy consumption for lighting	>45% reduction in EUI compared with code baseline lighting energy	79%			62%			43%		
		Yes			Yes			Yes in 80% of space		
Reduce lighting demand by better lighting design	>25% reduction in peak lighting power density (LPD) compared with code baseline LPD	60%			47%			52%		
		Yes			Yes			Yes		
Reduce carbon footprint of the lighting system	>45% reduction in carbon footprint compared to a building with code baseline lighting energy in the same region	79%			62%			43%		
		Yes			Yes			Yes in 80% space		
Cost effectiveness	Building size	Sm	Md	Lg	Sm	Md	Lg	Sm	Md	Lg
	>2 SIR over a 20 year period	1.6	2.8	3.4	1.8	2.8	4.4	1.2	1.6	2.4
		No	Yes	Yes	No	Yes	Yes	No	No	Yes
	<7 years payback	6.25	3.89	3.09	5.37	3.56	2.28	8.67	6.47	4.29
		Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes

With respect to system reliability, system maintainability, work plane illuminance, and ease of installation and commissioning, all three systems met the objectives with significant margin. Systems integration performance, or the effect of the lighting control systems on the HVAC load, as computed from Energy Plus model based simulations met the project objectives.

This demonstration project has shown that advanced lighting control systems deployed in existing DoD buildings can provide significant energy cost and carbon footprint reduction ranging from 43% to 79% depending on the building geometry, legacy system deployed, and usage pattern. For large buildings (over 100,000 square feet [ft^2]), networked systems such as the Dynalite or Hybrid ILDC, are expected to provide the best results whereas medium to small sized buildings standalone room based systems such as the OccuSwitch Wireless system would be more appropriate.

Following the encouraging results of this demonstration project, the Dynalite and the OccuSwitch wireless systems were introduced as commercial products in the U.S. market in 2010 and 2012, respectively.

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1.0 INTRODUCTION

According to the Energy Information Administration, lighting accounted for 37.6% of site electricity used in U.S. commercial buildings (2003). Advanced lighting controls offer one of the most cost-effective means to reduce energy, carbon footprint, and operating costs of buildings. Lighting controls regulate the timing and intensity of light in order to provide the right amount of light when and where it is needed in a cost-effective way. In addition to saving energy, advanced controls can improve occupant satisfaction by providing personal control over light conditions.

1.1 BACKGROUND

Lighting is one of the largest energy-consuming elements in most buildings at Department of Defense (DoD) installations. In large military installations, such as Ft. Hood in Texas, lighting represents around 28% and cooling represents 33% of the total electrical energy used (Akbari et al.).

Existing lighting systems at many DoD facilities tend to be older, unmetered, outdated and equipped with only manual switches at the room or area level resulting in energy waste, for instance, when lights are inadvertently left on in daylit or unoccupied areas. This not only contributes to wasted lighting energy but also increases the cooling load on air-conditioning systems, thereby compounding energy waste in buildings.

Lighting controls can have a large impact on these areas by reducing wasted lighting energy, reducing cooling loads, and improving occupant satisfaction and productivity. This can be accomplished by detecting occupancy, harvesting daylight, and exploiting integrated control strategies while enhancing user productivity and comfort. Furthermore, emerging communications technologies, particularly wireless, will reduce the cost of installing advanced lighting controls into older buildings typical of DoD inventory.

The selection of the best lighting control solution depends upon a number of factors such as building type, location, climate zone and usage profiles. Therefore, three complementary lighting control systems were deployed to meet DoD facility requirements.

1.2 OBJECTIVES OF THE DEMONSTRATION

The principal objective of this project is to quantify the energy, environmental, economic and user benefits of deploying advanced lighting control technologies at a representative U.S. Army installation (Ft. Irwin). In order to accomplish this goal, key lighting control strategies including scheduling, personalized dimming, daylight harvesting, occupancy sensing, and scene setting were implemented.

The offered system solutions were specifically tailored to suit the unique characteristics and operating conditions of the respective target facility. Technical challenges relating to robustness of the system and installation complexity affecting optimal cost/benefit trade-off of the featured solutions were addressed. The performance of each technology was evaluated in a variety of usage scenarios to judge the efficacy of each system. To verify the performance in DoD settings,

empirical evidence to evaluate energy savings, demand savings, cost-effectiveness, payback time, system reliability, system maintainability, ease of installation, and user satisfaction as a result of deploying these systems were gathered. Furthermore, using model-based simulations, the impact of the demonstrated lighting system on heating, ventilation and air conditioning (HVAC) energy was quantified. Results of the performance analysis are discussed in Section 6.

1.3 REGULATORY DRIVERS

DoD operates about 307,295 buildings spanning over 2.2 billion ft^2 of space. It spends about $3.784 billion on facilities energy. This enormous footprint offers large opportunities for energy and cost savings. To exploit those opportunities, a number of legislations, executive orders, and DoD directives have been issued that mandate significant energy efficiency improvements. The most significant ones are noted below:

- DoD Energy Manager's Handbook, 2005
- The Energy Policy Act of 2005
- Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding of 2006
- Executive Order 13423: Strengthening Federal Environmental, Energy, and Transportation Management of 2007
- The Energy Independence and Security Act of 2007
- Unified Facilities Criteria (UFC) 3-400-01 Energy Conservation, 2008
- Army Energy Security Implementation Strategy of 2009
- Executive Order 13514: Federal Leadership in Environmental, Energy and Economic Performance of 2009

The energy conserving methods demonstrated in this report are aligned with the U.S. Department of Energy's (DOE) Federal Energy Management Program (FEMP) Procurement Challenge, which offers incentives to Federal Energy Managers to comply with Executive Orders. In particular, these advanced lighting technologies will go a long way towards helping federal buildings, of which DoD's share is 66%, comply with Executive Orders 13423 that mandates 30% energy reduction in federal buildings by 2015 when compared to a 2003 baseline.

2.0 TECHNOLOGY

2.1 TECHNOLOGY OVERVIEW

2.1.1 Hybrid Integrated Lighting and Daylight Control (ILDC)

Functionality: Electric lighting control and daylight (blinds or shades) control are both essential for regulating interior lighting conditions. The Hybrid Integrated Lighting and Daylight Control (ILDC) system implements integrated control algorithms that integrate artificial light with daylight control, thereby fully optimizing energy savings while enhancing user comfort. The system combines user preferences with sensor readings (occupancy and light level) to harvest natural light through integrated control of motorized blinds and electric light. Additionally, integrated control reduces HVAC loads by optimizing solar gain and the thermal effects of electric lighting.

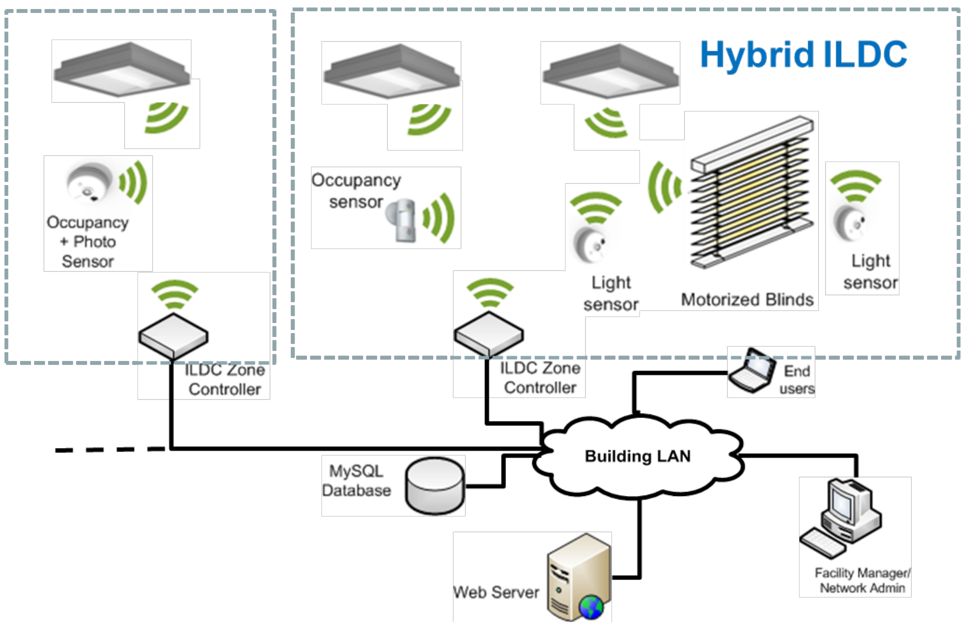

Figure 1. System architecture of Hybrid ILDC.

Architecture: The system features wireless connectivity among sensors and actuators within a zone and exploits wired connectivity across zones (thus "hybrid") to enable building-wide deployment. The combination of wireless and wired connectivity is an important aspect that makes the architecture more scalable. Each user's workstation is associated with corresponding sensors, window blinds and fixtures to enable personalized integrated control. Examples of user preferences include illuminance setpoints, glare trigger setpoints, light levels, blind heights, and slat tilt angles. The web system includes facility manager and network administrator specific web interfaces for supervisory and administrative controls.

Operation: Zone controllers combine sensor readings with user preferences to derive the optimal electric light levels and blind positions. The schematics of the ILDC control strategy are illustrated in Figure 2. The goal of an integrated control strategy is to maintain task illuminance

close to the desired set point in the occupied state while capitalizing on daylight and minimizing electric light utilization.

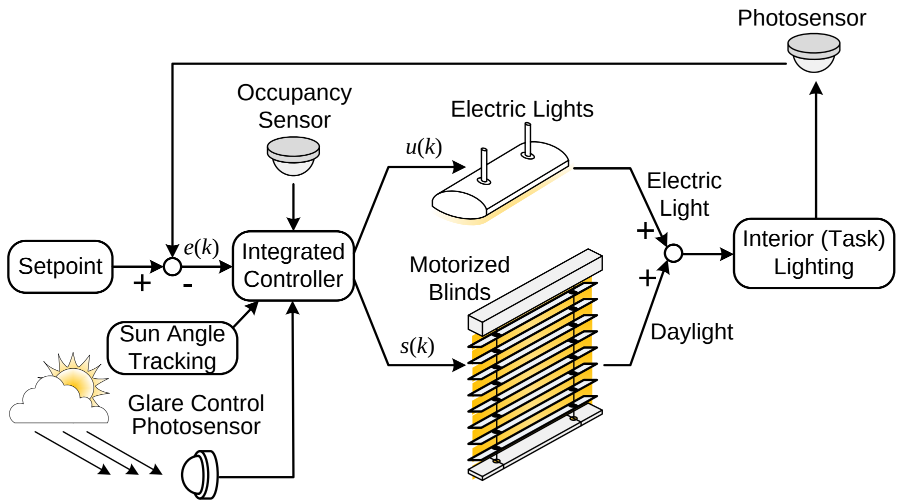

Figure 2. Schematics of the Hybrid ILDC system.

If the space is unoccupied, the lights are turned off. If the space is occupied, the blinds are opened to allow in daylight to an extent that does not cause discomfort (glare), while the lights are dimmed so that the overall illumination meets the user's requirements.

2.1.2 OccuSwitch Wireless

Functionality: OccuSwitch Wireless is a room-based lighting control system that uses a wireless multi-sensor to measure occupancy and light levels within the room and transmits that information to a wall-mounted dimmer switch that can switch ON and OFF or dim it to an appropriate level. The OccuSwitch dimmer controls the dimming ballasts installed in the ceiling fixtures directly over the in-place wiring.

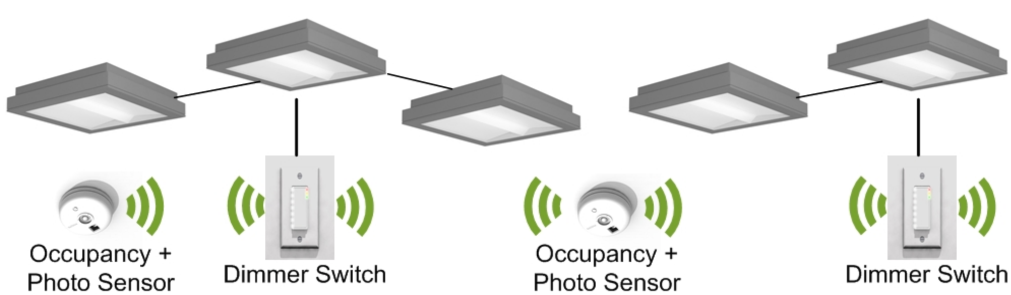

Figure 3. Schematic diagram of OccuSwitch Wireless.

Architecture: As shown in Figure 3, the system consists of two main components: a wall mounted dimmer switch and a battery-powered ceiling-mounted combination photo and occupancy sensor, which are interconnected using ZigBee PRO [3] wireless technology. The

dimmer switch controls line voltage (triac) dimming ballasts, which are compatible with standard ballasts, simplifying the retrofit. Multiple sensors and switches can be used to expand coverage.

Operation: Using a combination of passive infrared technology and advanced logic for detecting major and minor motion, the sensor recognizes when the room is occupied (or unoccupied). The light level reporting frequency is dynamically adapted to save battery energy. The occupancy sensor detects motion and the photosensor measures the light level; these are then communicated to the dimmer switch over the radio interface. When the space is unoccupied the lights are turned off. When the space is occupied the closed-loop feedback system regulates the light level close to the setpoint by dimming the artificial lights in proportion to available daylight.

2.1.3 Dynalite

Functionality: Dynalite is a distributed control based building-wide lighting control system offering scene settings, personalized dimming, scheduling, occupancy sensing and daylight harvesting. This system features the reliability offered by a wired solution, an intuitive user interface and an interface to Building Management Systems (BMS).

Architecture: The Dynalite system architecture for a multi-story application in which sensors, control panels, touch screens, time-clock, server personal computers (PC) and controllers are interconnected over an RS485 network to form a complete solution are outlined in Figure 4. Command and status information is passed to all devices over the network using the event-based DyNet protocol. The distributed processing architecture is robust against a single point of failure.

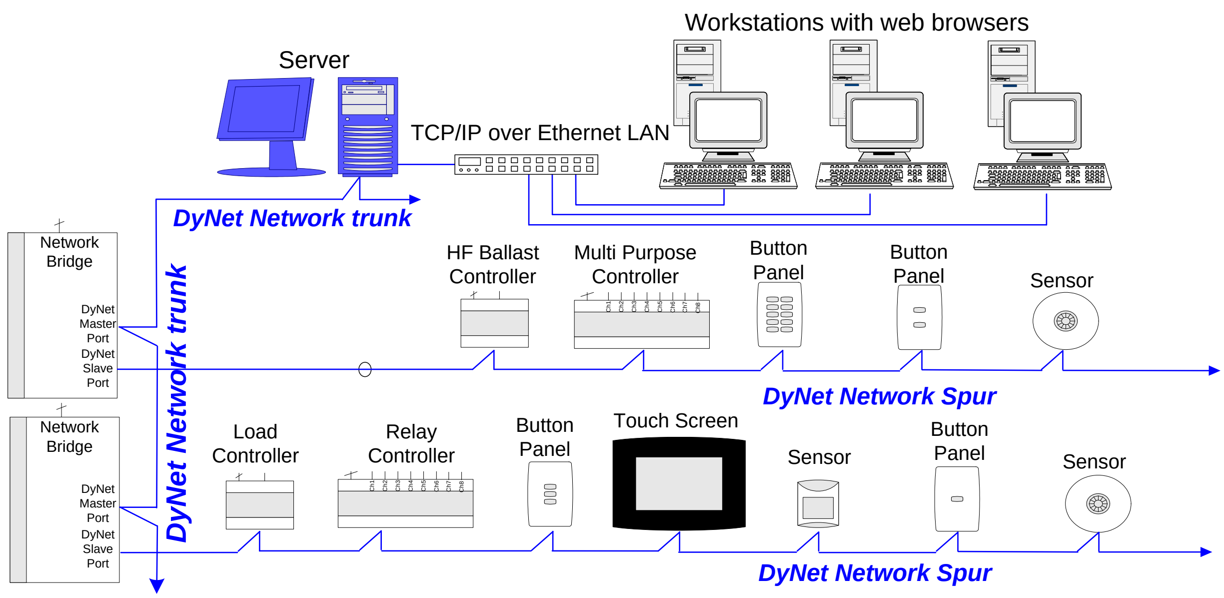

Figure 4. Architecture of the Dynalite system.

Operation: Dynalite's universal sensor combines motion detection, light level detection, and receiver (for remote control). Occupancy and light sensors work together in conjunction with time clocks to implement conditional logic control. When excess natural light is detected, the electric light is switched-off in the absence of motion, but when occupancy is detected then

electric light is dimmed to avoid shadowing and provide adequate horizontal illumination on desk surfaces. Dynalite implements time-schedule based controls to eliminate unnecessary lighting energy use outside 'normal' working hours (e.g., after hours, weekends, public holiday). If off-shift employees are detected then egress paths and common areas are illuminated. The time clock can be used to trigger events by time of day, sunrise or sunset, on a specific day of the week, or on a specific date.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The distinguishing characteristics of the three systems are presented in Table 2. By design, Hybrid ILDC is suitable only for perimeter areas in the building that receive the daylight. Compared to a conventional system, more skills are needed to configure and commission the integrated system.

Table 2. Key features of demonstrated systems.

	Hybrid ILDC	OccuSwitch Wireless	Dynalite
Control type	Integrated control of daylight and electric light; link to HVAC.	Electric light control	Electric light control integrated with BMS
Supported Sensors	Sunlight intensity sensor, light/occupancy/temp sensors	Light sensors and occupancy sensors	Ceiling mounted light /occupancy sensors
Scalability	Scalable from a single room to entire building	Room by room	Scalable from a single room to entire building
Best applications	Multi floor office buildings with daylight areas; retrofit or new	Single offices; barracks; retrofits; smaller budget	New construction, major renovation.
In-room Connectivity	Wireless based on ZigBee PRO standard	Wireless based on ZigBee PRO standard	Wired
Building-wide connectivity	Wired using internet protocol (IP) over Ethernet	Not applicable	Wired using RS 485
Cost advantage	++ Installation ++ Recommissioning	+++ Installation ++ Recommissioning	+ Installation +++ Recommissioning
Energy adv.	+++	++	++
Challenges	Building-wide interconnect	Optimal Sensor placement	Installation skills

The OccuSwitch system, with its modular room based or area based control is suitable for small buildings where full networking is not required. OccuSwitch wireless system demonstrated at Ft. Irwin does not support building-wide connectivity. Newer versions of OccuSwitch system currently in advanced stages of development are capable of providing building-wide connectivity and they can support centralized monitoring and control.

The Dynalite system, based on robust wired communication links, is optimized for new constructions or deep retrofit where the incremental cost of wiring is minimal since it can be done during and together with the wiring of the rest of buildings. However, as shown in this demonstration project, the system can be effectively implemented in building with drop ceilings as well.

3.0 PERFORMANCE OBJECTIVES

Below are terms used in Table 3, performance objectives.

Installed Lighting Power – The electrical power of all installed (hard wired) fixtures at full power, which includes the lamps, ballasts, and control devices. Installed lighting power is specified in Watts (W).

Code Baseline Lighting Power Density (LPD) – The maximum amount of Installed Lighting Power for all interior lighting systems in the target space per square foot of lighted floor area as allowed by the American National Standards Institute (ANSI)/American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE)/Illuminating Engineering Society of North America (IESNA) Standard 90.1-1989. LPD is specified in Watts/ft^2.

Code Baseline Lighting Energy Usage Intensity (EUI) – The amount of energy used for interior lighting systems using the Code Baseline LPD and the estimated lighting schedules. This metric is determined as the product of the lighted hours per workday, number of workdays per year and Code Baseline LPD. In this report we assume that on an average the lights are on for 10 hours per working day and 251 workdays in a year. EUI is specified in kilowatt hour (kWhr)/ft^2/year.

Peak Lighting Power – The peak lighting power measured on all lighting circuits averaged over the data recording period of 15 minutes, recorded over study period. Peak lighting power is specified in Watts.

Peak LPD – The Peak Lighting Power in the building or building space per unit of lighted floor area. Peak LPD is specified in watts/ft^2.

Downtime – The time duration when the lighting control system is non-responsive to manual on-off commands.

Table 3. Performance objectives.

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Reduce electrical energy consumption for lighting	EUI as kWhr/ft^2/year	Metered electricity usage after lighting control installation and code baseline lighting energy	>45% reduction in EUI compared with code baseline lighting energy
Reduce lighting demand by better lighting design	Peak LPD as watts/ft^2	Metered data on peak lighting power, fixture data, floor plans and code baseline LPD	>25% reduction in Peak LPD compared with code baseline LPD
Reduce carbon footprint of the lighting system	MMT/ft^2/year	Electrical energy savings and sources of electrical energy at Ft. Irwin	>45% reduction in carbon footprint compared to a building with code baseline lighting energy in same region
Cost-effectiveness	SIR over a 20 year period	Data on cost elements mentioned in Table 10 including historical energy cost, energy use, operating cost savings	>2 SIR over a 20 year period
	Simple Payback		<7 years payback
System reliability	System uptime	System failure notifications	No more than three system-wide failures per system in a 3-month time window
System maintainability	Number of scheduled maintenance outages and average length	Number of scheduled maintenance actions and downtime	No more than four scheduled maintenance actions per system per month and no more than 8 hours of scheduled maintenance downtime per system per month.
	Number of unscheduled maintenance outages and average length	Number of unscheduled maintenance actions and downtime	No more than two unscheduled maintenance actions per system per month and no more than 4 hours of unscheduled maintenance downtime per system per month
Work plane illuminance	1-foot candle on work plane	Measured artificial light illuminance level on work plane before and after lighting control installation	>10% reduction in average deviation from Directorate of Public Works (DPW) requirement over the average deviations prior to upgrade.
Qualitative Performance Objectives			
Ease of installation and commissioning	Ability of installers to quickly install and commission the system	Feedback from installers on time required to install and commission system	Installer survey indicates that installers can install and commission systems with minimal training
User satisfaction	Level of satisfaction among users on the performance of the technology	Occupant surveys on comfort, convenience, and satisfaction with lighting and controls	User satisfaction survey indicates improved satisfaction with performance
System integration	Impact of the lighting system on HVAC energy usage	Code baseline LPD, post-retrofit lighting LPD and EnergyPlus model	>5% reduction in HVAC energy compared with code baseline HVAC energy

MMT – Million Metric Tons
S1R – Savings to investment ratio
1-foot candle = 1 lumen

4.0 SITE DESCRIPTION

4.1 FACILITY/SITE LOCATION AND OPERATIONS

The Project Team worked with DPW to identify suitable buildings for each technology.

1. Hybrid ILDC system demonstration was carried out in a section of the Building 279 covering about 1782 ft^2.
2. OccuSwitch Wireless system demonstration was carried out in Building 602, covering almost the entire building 4821 ft^2.
3. Dynalite system demonstration was carried out in a portion of the Building 988, covering approximately 7177 ft^2 out of the total building area of 22,000 ft^2.

4.2 FACILITY/SITE CONDITIONS

4.2.1 Hybrid ILDC System Demonstration Site

The building chosen for the Hybrid ILDC demonstration is a fairly old (constructed in 1950s) administrative building. The project team targeted a 1782 ft^2 section of the building made up of eight offices—some private and some with two or three occupants—and one conference room. A simplified floor plan of the target space and fixture layout is shown in Figure 5.

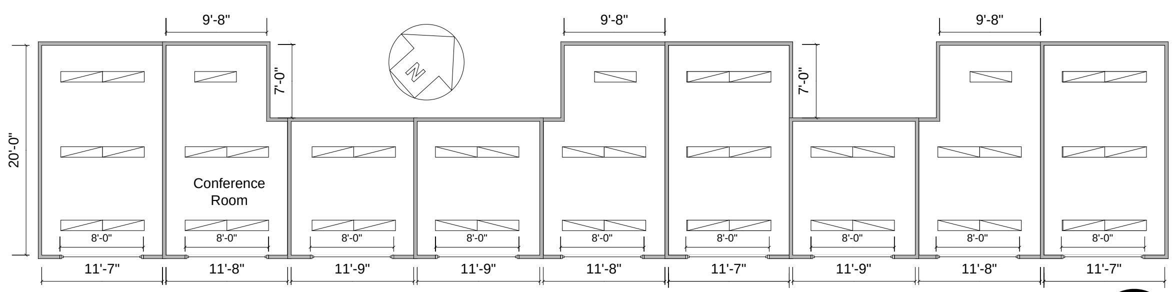

Figure 5. Simplified layout of the target space in building 279.
(dimensions are approximate)

The target rooms featured only manual on-off switches at the room level. Each room targeted for retrofit has large 8 ft by 5 ft windows facing southeast that provide abundant daylight. Most rooms had worn vertical blinds. Some rooms have a fraction of window obstructed due to window mounted air conditioning units. The building has a hard ceiling, which makes wireless technology a preferred option for retrofit.

The section of the building chosen for the demonstration had 45 fluorescent T8, 32W 2-lamp fixtures. A total of 42 fixtures were attached end to end in pairs, with each pair driven by a single 4-lamp fixed output electronic ballast. The remaining three fixtures were driven by 2-lamp fixed output electronic ballasts. Physical inspection of the lamps revealed that only about 54 lamps were operational out of the 90 installed lamps, probably due to a lack of maintenance.

All burned out lamps were replaced prior to the baseline monitoring period. The power supply is 120 Volts alternate current (AC).

The building is occupied by rotational units, with some occupants leaving for a new location after several months. Site visits and conversations with occupants suggested that while occupants perform typical office work while at their desks, work schedules often vary considerably day to day and week to week.

4.2.2 OccuSwitch Wireless Demonstration Site

The building chosen for the OccuSwitch demonstration is a fully occupied single story office building with hard ceiling, which makes wireless technology a preferred option for retrofit. It has 14 private offices, a conference room, a library, a mechanical room, a breakroom, two restrooms, and two utility areas with exterior access. The remaining area in the center contains open plan cubicles. There are 19 windows measuring 3 ft 4-inch by 2 ft on the periphery, resulting in a window to wall ratio of about 4%. Each private office has one small window that provides limited daylight, while the interior open plan office area has negligible daylight.

The project team targeted 4821 ft^2 of the floor area (out of total 5000 ft^2) for lighting upgrades covering the entire building except for exterior utility rooms. Of this area, 4375 ft^2 are included in all energy analysis. A circuit including the exterior utility rooms, the bathroom, and the break room was excluded from analysis due to extremely different pre-retrofit and post-retrofit use patterns in the exterior utility areas, which were not included in the retrofit.

The pre-retrofit lighting system consisted of 101 fluorescent T8 32W 4-lamp fixtures which that driven by fixed light output ballasts. A large number of lamps were intentionally removed from fixtures to save energy, causing distorted light distributions. Physical inspection revealed that only 201 lamps were installed and operational out of 404 potential lamps, bringing the installed LPD to 1.43W/ft^2 out of a possible 2.46W/ft^2 (based on benchtop measurements discussed later). The power supply is 120 Volts AC. The building had only manual on-off switches.

4.2.3 Dynalite Demonstration Site

The current command headquarters, Building 988, is the selected site for the Dynalite system. It is a single story administrative building that had only manual on-off switches prior to retrofit. [It comprises of a variety of room types such as private offices, open plan offices, conference rooms, a surveillance room, a theater, a storage room, and a copy room.] The building has a standard drop ceiling, which makes it appropriate for the Dynalite system that requires physical cabling to network together the luminaires, sensors, and controllers.

The project team selected approximately 7177 ft^2 of Building 988 consisting of 7 private offices, 1 open plan office, 1 conference room, 1 surveillance room, 1 theater, 1 lobby, 2 restrooms, 1 storage room and 1 copy room. The pre-retrofit lighting in target area consists of 85 fluorescent T8 32W 3-lamp fixtures and 6 T8 32W 2-lamp fixtures driven by fixed output ballasts. Some areas of the building were delamped to conserve energy. Before the retrofit only 237 lamps were installed out of 267 potential lamps. The open plan office area had light levels well below the

code requirements causing occupants to complain about the existing lighting conditions. The power supply is 277 Volts AC.

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5.0 TEST DESIGN

5.1 BASELINE CHARACTERIZATION

5.1.1 Code Baseline

The code baseline LPD is the installed lighting power for the lighting systems in the selected space per square foot of lighted floor area as allowed by the lighting code. The code baseline lighting EUI is determined as the product of the lighted hours per workday, number of workdays per year and the Code Baseline LPD. It was assumed that on average the lights are on continuously for 10 hours per day on weekdays and remain off during weekends and holidays. Furthermore, to derive annual EUI, 251 weekdays per year are assumed. The Unit Lighting Power Allowance specified in ANSI/ASHRAE/IESNA Standard 90.1-1989 is 1.81 W/ft^2 for office buildings having gross lighted areas in the range of 2001 to 10,000 ft^2. This results in a code baseline annual EUI of 4.54 kWhr/ft^2/year. In this report, the code baseline refers to this baseline. In order to compare the results with more recent code requirements, another reference was defined based on the ANSI/ASHRAE/IESNA Standard 90.1-2007. In this standard, the whole building LPD allowance for office spaces is specified as 1 W/ft^2. Based on 1 W/ft^2 LPD, 10-hour work day and 251 workdays a year, the annual EUI is estimated to be 2.51 kWhr/ft^2/year. In the remainder of the report we refer to this as the 2007 code reference.

5.1.2 Pre-Retrofit Metered Lighting Energy Use in Building 279

The pre-retrofit metered dataset had an average weekday EUI of 4.94 Wh/ft^2/day, weekend EUI of 0.75 Wh/ft^2/day, and holiday EUI of 0.72 Wh/ft^2/day. Annual EUI was calculated from these values based on an assumed annual distribution of 251 weekdays, 104 weekend days, and 10 holidays per year. This resulted in an annual EUI of 1.33 kWhr/ft^2/year. For each week of data, the peak LPD averaged over a 15 minute interval was calculated for the study area as a whole. The maximum peak LPD from the pre-retrofit metered dataset is 1.26 W/ft^2.

5.1.3 Pre-Retrofit Illuminance Characterization in Building 279

A pre-retrofit light survey was carried out on January 24, 2011 between 8:00 pm and 9:00 pm. Workplane illuminance levels were measured throughout the study areas (2 to 4 measurements on desks per room, resulting in 29 measurements overall). Despite installed low-ballast factor ballasts, illuminance levels were quite high, with measured values ranging from 520 to 958 lux.

5.1.4 Pre-Retrofit Metered Lighting Energy Use in Building 602

The pre-retrofit metered dataset had an average weekday EUI of 7.01 Wh/ft^2/day, weekend EUI of 0.18 Wh/ft^2/day, and holiday EUI of 3.36 Wh/ft^2/day. This resulted in an annual EUI of 1.81 kWhr/ft^2/year. The 15 minute peak LPD for pre-retrofit metered dataset is 1.14 W/ft^2.

5.1.4.1 Adjusted Pre-Retrofit Lighting Energy Use in Building 602

During the retrofit, lamps were shifted from their initial uneven distribution to a layout with two lamps in each fixture. Although almost the same number of lamps operated in pre-retrofit and post-retrofit periods (201 and 202, respectively), a large number of lamps were moved from

private office areas on the periphery to open office areas where de-lamping had been more extensive. Because the open office areas have much longer operating hours and higher energy use than the perimeter spaces, this shift alone increased building's overall lighting energy use. To eliminate this effect and isolate the savings associated with the lighting controls, an adjusted pre-retrofit was calculated from the pre-retrofit metered dataset. This adjusted pre-retrofit estimates what energy use would have been with identical baseline use patterns but with the post-retrofit installed lamp layout. The adjusted pre-retrofit has a calculated weekday EUI of 8.59 $Wh/ft^2/day$, weekend EUI of 0.25 $Wh/ft^2/day$, and holiday EUI of 4.72 $Wh/ft^2/day$. This results in an annual EUI of 2.23 $kWhr/ft^2/year$. The peak LPD for a 15 minute interval over the pre-retrofit study period is 1.17 W/ft^2 for the adjusted pre-retrofit.

5.1.5 Pre-Retrofit Illuminance Characterization in Building 602

A pre-retrofit light survey was carried out on January 10, 2011 between 8:00 pm and 10:00 pm. Illuminance levels were measured throughout the study areas (37 measurements overall). Unfortunately, due to contractor's oversight, many measurements were taken at floor level rather than at the workplane; these were included in analysis nonetheless. Illuminance levels were quite extreme, with measured values ranging from very low (22.4 lux) to extremely high (1662 lux).

5.1.6 Pre-Retrofit Metered Lighting Energy Use in Building 988

The pre-retrofit dataset had an average weekday EUI of 8.02 $Wh/ft^2/day$, weekend EUI of 3.77 $Wh/ft^2/day$, and holiday EUI of 5.06 $Wh/ft^2/day$. This resulted in an annual EUI of 2.46 $kWhr/ft^2/year$. The maximum 15 minute peak LPD for pre-retrofit metered dataset is 0.77 W/ft^2.

5.1.6.1 Adjusted Pre-Retrofit Lighting Energy Use in Building 988

During the retrofit, several areas where lamps had been removed were re-lamped. In particular, the large open office area three lamp fixtures was de-lamped to two lamps per fixture. Delamping reduced illuminance levels and caused occupant complaints about light conditions. To address this, three lamps per fixture were installed during the retrofit. Further, pre-retrofit fixed output ballasts with fairly low ballast factors (0.9 and 0.88) were replaced with dimmable ballasts with higher ballast factors of 1.0. This increased the available light output but also increased the installed operating power. Finally, four parabolic lensed troffer 3-lamp fixtures were installed in the surveillance room to address glare. The adjusted pre-retrofit has a calculated weekday EUI of 12.14 $Wh/ft^2/day$, weekend EUI of 5.76 $Wh/ft^2/day$, and holiday EUI of 7.73 $Wh/ft^2/day$. This results in an annual EUI of 3.73 $kWhr/ft^2/year$. The peak LPD over a 15 minute interval is 1.11 W/ft^2 for the adjusted pre-retrofit dataset.

5.1.7 Pre-Retrofit Illuminance Characterization in Building 988

A pre-retrofit light survey was carried out on December 20, 2010 after 7:00 pm. Illuminance levels were measured throughout the study areas (32 measurements overall). Of these measurements, ten were taken in private offices and six in the open office area; other measurements were not included in analysis. Unfortunately, two open office measurements were taken at floor level rather than at the workplane, these were included nonetheless. Illuminance levels varied widely but were mostly above 500 lux in private offices and between 300 and 400 lux in the open office.

5.2 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

5.2.1 Hybrid ILDC

A total of 45 existing 2-lamp fixtures operated with fixed output ballasts were replaced by 45 new Wrap 9 inch by 48 inch Prismatic Surface Wrap Lens fixtures made by Philips. Each fixture was equipped with a 2 by 28T5/UNV DIM universal dimmable ballast, which operates with 64W input power and a ballast factor of 1.0. The fixture was custom fitted with a ZigBee radio module, a 0-10 Volt ballast controller and accessories (e.g., power adapter and relay switch), which increased input power by approximately 2W. Additional equipment including nine motorized venetian blinds, 24 ceiling mounted wireless occupancy and light sensors, nine window mounted photo sensors, nine zone controllers, nine touch screen control panels, database, uninterruptible power supply (UPS), Ethernet Switches and CAT5e cables were installed. Pre-retrofit, post-retrofit, and tuned installed LPDs are summarized in Table 4.

Table 4. Summary of installed lighting system and LPD in building 279.

	Pre-Retrofit	Post-Retrofit Installed	Post-Retrofit Tuned
Lamp type (2 lamps per fixture)	F32T8	F28T5	F28T5
Number of fixtures	45	45	45
Installed power (W)	2547	2880	1620
Floor area (ft^2)	1782	1782	1782
Installed LPD (W/ft^2)	1.43	1.62	0.91

5.2.2 OccuSwitch Wireless

A total of 101 existing 4-lamp T8 fixtures were converted to 2-lamp dimming fixtures. Each fixture was equipped with a 2-lamp line voltage (triac) dimming ballast and two T8 Cool White (4100K, 85 CRI) 32W Philips fluorescent lamps. The installed power after the retrofit was 68W per fixture. Control equipment, including 31 ceiling-mounted wireless occupancy and light sensors, 27 dimmer wall switches (adding three new gang single gang locations), and three dimming power extenders were installed. Pre-retrofit delamped, and post-retrofit installed LPDs are summarized in Figure 5.

Table 5. Summary of installed lighting system and LPDs in building 602.

	Pre-Retrofit Delamped	Post-Retrofit/Installed
Lamp type	F32T8	F32T8
Number of lamps	201	202
Installed power (W)	5536	5440
Floor area (ft^2)	3723	3723
Installed LPD (W/ft^2)	1.49	1.46

5.2.3 Dynalite

A total of 85 existing fluorescent T8 32W 3-lamp fixtures operated with fixed output ballasts were converted to 3-lamp dimming fixtures. Each fixture was equipped with a 3-lamp DALI dimming ballast. Each fixture housed three T8 Cool White (4100K, 85 CRI) 32W Philips fluorescent lamps. The existing six T8 32W 2-lamp fixtures driven by fixed output ballasts were converted to DALI dimming ballasts. These fixtures were fitted with two T8 Cool White (4100K, 85 CRI) 32W Philips lamps. Four new 3-lamp DALI ballast driven fixtures were installed in surveillance room to address glare issue. Additional equipment including 31 ceiling mounted occupancy and light sensors, 17 wall stations, 1 DALI load controller, 1 DALI sniffer, 1 server PC, Dynet cables and DALI cables were also installed. Pre-retrofit delamped and post-retrofit installed LPDs are summarized in Table 6.

Table 6. Summary of installed lighting system and LPDs in building 988.

	Pre-Retrofit Delamped	Post-Retrofit Installed
Lamp type	F32T8	F32T8
Number of lamps	228	279
Installed power (W)	6717	9409
Floor area (ft^2)	7177	7177
Installed LPD (W/ft^2)	0.94	1.31

5.3 SAMPLING PROTOCOL

All energy calculations were based on the following assumptions:

- The carbon footprint of lighting energy usage is derived using the annual non-baseload output emission rates applicable to Ft. Irwin. In the Western Electric Coordinating Council (WECC) California sub-region, the annual non-baseload output emission rates for carbon dioxide (CO_2) is 1.045 lb/KWh (Year 2007 Green House Gas [GHG] Annual Output Emission Rates, Environmental Protection Agency [EPA]).
- The Illuminating Engineering Society of North America (IESNA) recommended workplane illuminance is 500 lux for private offices and 300 lux for open office cubicles. These are also DPW's illuminance requirements. Since a certain amount of illuminance variation can occur without negatively affecting occupants, this analysis used a target illuminance range to evaluate light levels. The range was defined based on the understanding that a proportional rather than absolute increase and decrease in illuminance will have roughly equivalent effect on an occupant:
  - The acceptable range is defined as illuminance levels of [2t/3, 3t/2], where t is the target illuminance (500 lux or 300 lux). This makes the acceptable range 333-750 lux in private offices and conference rooms and 200-450 lux in open office spaces.

6.0 PERFORMANCE ASSESSMENT

As stated in the executive summary, the lighting control systems were designed, developed and deployed by Philips. All performance measurements, interpretation and analysis were carried out independently by Lawrence Berkeley National Laboratory (LBNL) as reported in this section.

6.1 ENERGY PERFORMANCE SUMMARY FOR ALL MONITORED BUILDINGS

The energy performance measured in Buildings 279, 602 and 988, before the lighting controls retrofits (the pre-retrofit period) and during the post-retrofit period immediately after the controls installation, is summarized in Table 7 and Table 8.

Table 7. Energy performance results.

	Building	279	602	988
Weekday EUI (Wh/ft^2/day)	Pre-retrofit metered	4.94	7.01	8.02
	Adjusted pre-retrofit	N/A	8.59	12.14
	Code baseline	18.1	18.1	18.1
	Post-retrofit metered	3.28	6.71	8.68
Weekday EUI percent savings	Pre-retrofit metered	33.7%	4.3%	-8.2%
	Adjusted pre-retrofit	N/A	22.0%	28.5%
	Code baseline	81.9%	62.9%	52.0%
Annual EUI (kWhr/ft^2/year)	Pre-retrofit metered	1.33	1.81	2.46
	Adjusted pre-retrofit	N/A	2.23	3.73
	Code baseline	4.54	4.54	4.54
	Post-retrofit metered	0.96	1.74	2.60
Annual EUI percent savings	Pre-retrofit metered	27.7%	4.2%	-5.7%
	Adjusted pre-retrofit	N/A	22.2%	30.3%
	Code baseline	78.9%	61.8%	42.8%

Table 8. Peak LPD results.

					Percent Savings Compared To		
	Pre-Retrofit Metered	Adjusted Pre-Retrofit	Code Baseline	Post-Retrofit Metered	Pre-Retrofit Metered	Adjusted Pre-Retrofit	Code Baseline
Building 279 Peak LPD (W/ft^2)	1.26	N/A	1.81	0.73	42%	N/A	60%
Building 602 Peak LPD (W/ft^2)	1.14	1.17	1.81	0.96	16%	18%	47%
Building 988 Peak LPD (W/ft^2)	0.77	1.11	1.81	0.86	-12%	23%	52%

6.1.1 Reduced Lighting Demand in Building 279

The goal was to demonstrate at least a 25% reduction in peak LPD compared to code baseline. The results show 60% savings over code baseline, substantially exceeding the target. The retrofit also resulted in a peak LPD 42% lower than the pre-retrofit metered peak and 27% lower than a

code baseline peak corresponding to 2007 reference code requirements. Mean weekday metered LPDs for the pre-retrofit and post-retrofit study periods are shown in Figure 6. Post-retrofit LPDs in particular are extremely low.

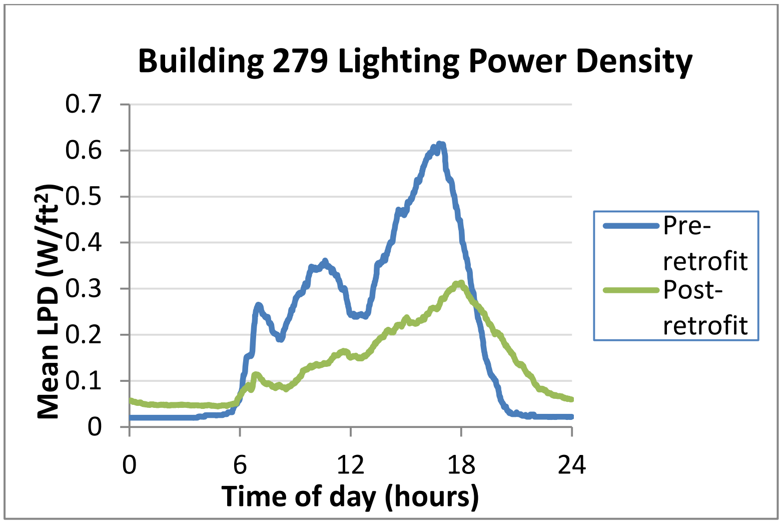

Figure 6. Building 279 mean weekday metered LPD during the pre-retrofit and post-retrofit.

6.1.2 Reduced Lighting Demand in Building 602

The results show 47% savings compared to the code baseline, substantially exceeding the target. Mean weekday LPDs over the course of the day for the pre-retrofit and post-retrofit study periods are shown in Figure 7.

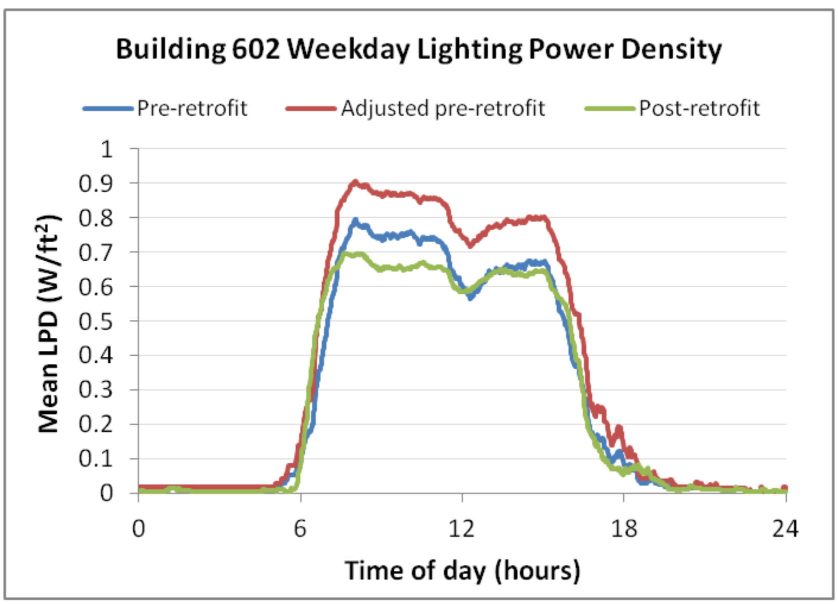

Figure 7. Building 602 mean weekday LPD for pre-retrofit, adjusted pre-retrofit, and post-retrofit.

6.1.3 Reduced Lighting Demand in Building 988

The results show a 52% reduction compared to the code baseline, substantially exceeding the target. The retrofit also resulted in a 23% reduction compared to the adjusted pre-retrofit and a 14% reduction compared to the 2007 reference code level.

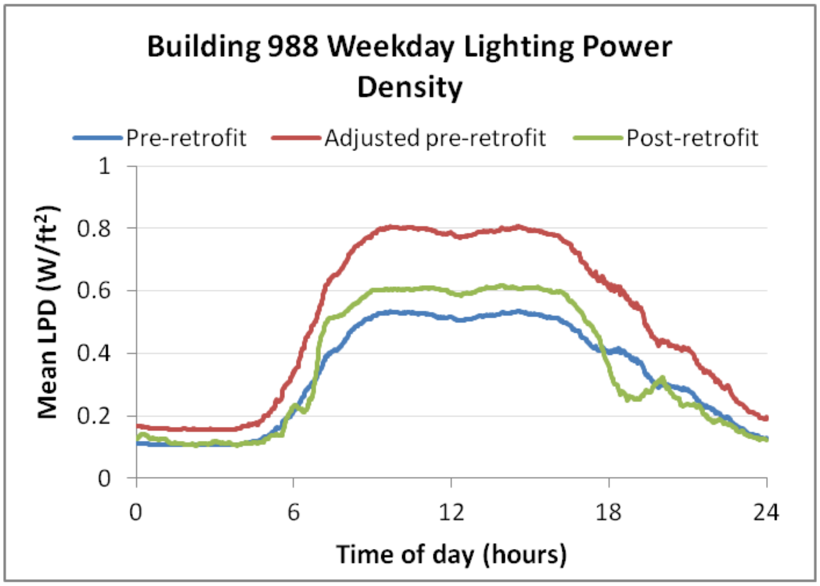

Figure 8. Building 988 mean weekday LPD for pre-retrofit, adjusted pre-retrofit, and post-retrofit.

6.2 PERFORMANCE RESULTS SUMMARY

The performance of three technologies against the objectives stated in Table 3 are summarized in Table 9. As shown in the table, most of the objectives were met during the demonstration, with exception of two that are discussed below.

Table 9. Performance results.

Performance Objective	Success Criteria	Results		
		Hybrid ILDC	OccuSwitch	Dynalite
Reduce electrical energy consumption for lighting	>45% reduction in EUI compared with code baseline lighting energy	79%	62%	43%
		Yes	Yes	Yes in 80% space
Reduce lighting demand by better lighting design	>25% reduction in peak LPD compared with code baseline LPD	60%	47%	52%
		Yes	Yes	Yes
Reduce carbon footprint of the lighting system	>45% reduction in carbon footprint compared to a building with code baseline lighting energy in the same region	79%	62%	43%
		Yes	Yes	Yes in 80% space

Table 9. Performance results (continued).

Performance Objective	Success Criteria	Results								
		Hybrid ILDC			**OccuSwitch**			**Dynalite**		
Cost-effectiveness	Building size	Sm	Md	Lg	Sm	Md	Lg	Sm	Md	Lg
	>2 SIR over a 20 year period	1.6	2.8	3.4	1.8	2.8	4.4	1.2	1.6	2.4
		No	Yes	Yes	No	Yes	Yes	No	No	Yes
	<7 years payback	6.25	3.89	3.09	5.37	3.56	2.28	8.67	6.47	4.29
		Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
System reliability	No more than three system-wide failures per system in a 3-month time window	0			0			0		
		Yes			Yes			Yes		
System maintainability	No more than four scheduled maintenance actions per system per month and no more than 8 hours of scheduled maintenance downtime per system per month.	<=1/mo			<=2/mo			<=1/mo		
		0 hr			0 hr			0 hr		
		Yes			Yes			Yes		
	No more than 2 unscheduled maintenance actions per system per month and no more than 4 hours of unscheduled maintenance downtime per system per month	<=1/mo			<=1/mo			<=1/mo		
		0 hr			0 hr			0 hr		
		Yes			Yes			Yes		
Work plane illuminance	>10% reduction in average deviation from the DPW requirement over the average deviations prior to upgrade.	98%			73%			69%		
		Yes			Yes			Yes		
Ease of installation and commissioning	Installer survey indicates that installers can install and commission systems with minimal training	Yes			Yes			Yes		
User satisfaction	User satisfaction survey indicates improved satisfaction with performance	Statistically insignificant responses								
System integration	>5% reduction in HVAC energy compared with code baseline HVAC energy	7.7% – 15.6%			11.6%			8.4%		
		Yes			Yes			Yes		

As shown in Table 9, the three systems performed differently with respect to energy savings as expressed in EUI/carbon footprint reduction, peak LPD and cost effectiveness. This is partly due to the differences in the characteristics of the buildings they were deployed in and partly due the energy savings features of the systems. For instance, the size of the buildings is an important parameter that determines the system cost per unit area as fixed hardware cost, such as servers and controllers are amortized over the entire area.

To provide a more generalized picture that can be applied across the entire DoD facilities, three different building size scenarios have been considered—small, medium and large—defined specifically in Section 7.4. With this classification, it is seen that payback <7 years is met in most cases with the exception of the small area category for Dynalite system. Savings to investment ratio objective (>2) is met in the large buildings for all three systems and medium buildings for Hybrid ILDC and OccuSwitch systems. In small buildings, the SIR objective is not met.

While on average the performance for the three systems well exceeded the key targets (energy cost and carbon footprint), the Hybrid ILDC and OccuSwitch systems met or exceeded these key performance objectives. Dynalite achieved 43% reduction in EUI compared with code baseline lighting energy against the target of at least 45% reduction in EUI, marginally falling short of the target.

It is worth mentioning that in one of the areas in building 988, three ballasts were inadvertently replaced without our knowledge and lights were left on at full power for nearly 3 weeks. This error increased overall weekday energy use by nearly 5%. In spite of that, in 80% of the circuits serving the areas, the energy savings success criteria were met. So overall, it is expected that had the Dynalite lighting controls been implemented in the entire building and the error in ballast replacement were not made, the energy savings average would have been higher exceeding the target of 45% savings over code baseline.

With respect to system reliability, system maintainability, work plane illuminance, and ease of installation and commissioning, all three systems met the objectives with significant margin. This is a testimony to the robustness of the systems in general and are independent of building characteristics.

Unfortunately, results of the user satisfaction survey were statistically insignificant. DPW was only able to identify four occupants for the user satisfaction survey in Building 279 during both pre-retrofit and post-retrofit study periods. Out of four occupants who were sent survey questionnaires, one person responded to the survey during the pre-retrofit period, and two responded during the post-retrofit period. In building 988, only four out of eight occupants responded to the pre-retrofit survey, and only one out of nine responded to the post-retrofit survey. DPW did not send a reminder email to post-retrofit occupants out of concern about disturbing them. The extremely low number of people surveyed limited the extent to which results can be considered representative.

Overall this demonstration project has shown that advanced lighting control systems deployed in existing DoD buildings can provide significant energy cost and carbon footprint reduction ranging from 43% to 79% depending on the building geometry, legacy system deployed and usage pattern. The three systems varied in terms of features and performance, each one being optimal for a certain class of building. For large buildings (over 100,000 ft^2) networked systems such as the Dynalite or Hybrid ILDC are expected to provide the best results, whereas for medium to small sized buildings standalone room based systems such as the OccuSwitch Wireless system would be more appropriate.

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7.0 COST ASSESSMENT

7.1 COST MODEL

The cost model developed for analysis encompasses design, material acquisition, installation, commissioning, supervision, inspection and cost of maintaining lighting control systems. The relevant cost elements and data tracked during the demonstrations are mentioned in Table 10.

Table 10. Cost model for the lighting control system.

Cost Element	Description	Data Tracked During the Demonstration
Design	Developing design documents and layout plans for the installation of lighting control system	10% of total investment in technology as recommended by building life-cycle cost (BLCC)
Hardware material costs	Capital costs of hardware used in the demonstration	Control equipment (e.g., sensors, ballast controllers, dimmers, switches, control panels) quantities and costs
		Lamps and fixtures quantities and costs
		Blinds and accessories quantities and costs
		Computer and software itemized costs
		Networking gear (e.g., ethernet switches, zone controllers) quantities and costs
		Cables, materials, and supplies
Installation costs	Labor required to install and wire the system	Installation labor rate ($/hr)
		Installation time
		Installation supplies and material cost
Commissioning cost	Labor required to commission and test the system	Hours spent on commissioning and testing
		Labor rate for commissioning and testing in ($/hr)
		Commissioning tools and supplies cost
Supervision, inspection and overhead	Cost of supervising and inspecting the lighting systems and associated overheads	6% of total investment in technology as recommended by BLCC
Base electric energy costs	Cost of energy used to power lighting systems	Unit electric energy prices ($/kWhr)
		Energy price projections published annually on April 1 by DOE in *Discount Factors for Life-Cycle Cost Analysis, Annual Supplement to NIST Handbook 135*.
		Baseline and post retrofit lighting energy usage data (kWhr/year)
Electric energy costs due to demand charges	Peak demand charges for the electrical energy used to power lighting systems	Demand charges ($/KW)
		Baseline and post-retrofit peak lighting demand (W)
HVAC energy cost savings	HVAC energy cost savings due to lighting upgrades	Simulation results on HVAC energy savings due to lighting upgrades (kWhr)
Utility rebates/ incentives	Utility rebates for upgrading the lighting system	Utility rebate for upgrading the lamp ($/lamp)
		Utility rebate for upgrading the fixture ($/fixture)
		Utility rebate for upgrading the sensor ($/sensor)

Table 10. Cost model for the lighting control system (continued).

Cost Element	Description	Data Tracked During the Demonstration
Maintenance costs	Cost of replacing lamps and batteries; cost of upgrading software	Lamp life (hours)
		Lamp quantity
		Cost of a new lamp ($/lamp)
		Lamp replacement labor rate ($/lamp)
		Lamp hazardous waste handling fee ($/lamp)
		Average hours of operation per year (hours)
		Average number of lamps replaced per year
		Amortized cost of initial group replacement
		Battery lifetime (years)
		Battery quantity
		Cost of a new battery
		Battery replacement labor cost
		Battery replacement cycles
		Software upgrade costs ($/year)
System Lifetime	Service life of lighting control system	20 years

7.2 COST ESTIMATES

The cost analysis assumes widespread deployment (at least few million ft^2) using commercial versions by the DoD. In this case, scale can allow for favorable pricing of material and labor and a more direct sales approach for the entire retrofit project including all aspects (material, installation, and commissioning).

7.2.1 Estimated Investment

The best available estimates for the cost of the technology in 2012 are used as inputs to derive the total investment in technology. Capital, installation and commissioning costs are added to compute total construction cost. On top of construction cost, 6% and 10% of total investment are added for supervision, inspection, and overhead (SIOH) cost and design cost respectively as recommended by the National Institute of Standards and Technologies' (NIST) BLCC Military Construction (MILCON) Energy Conservation Investment Program (ECIP) to identify the first cost. We calculated the rebate available for upgrading the existing lighting system to a new lighting control system using the Lighting Rebate Catalog of Southern California Edison (SCE) Company. Subtracting the utility rebate from the initial cost results in net investment. These estimated costs for three technologies are listed in Table 11.

Table 11. Net investment in technology.

Cost Elements	Units	Hybrid ILDC	Dynalite	OccuSwitch
Initial cost (design+ capital+ installation+ commissioning+ SIOH)	$/ft^2	6.7	5.04	4.14
Utility rebate	$/ft^2	1.05	0.5	0.75
Net investment (first cost – utility rebate)	$/ft^2	5.64	4.54	3.4

Below we compare the energy and maintenance costs of operating the legacy lighting system with those for upgraded lighting control system.

7.2.2 Estimated Energy Cost Saving

The electric energy rate schedule sourced from SCE which supplies power to Ft. Irwin, is used in life cycle cost estimates. The SCE's General Service Rate Schedule (GS-2), which is offered to medium-sized commercial and industrial customers with demands above 20 kilowatts (kW) and below 200 kW, was found suitable for this analysis. Specifically, we used non time of use (TOU) rates that went into effect on March 1, 2011 (Cal. PUC Sheet No. 48082-E). This schedule has following main components:

- A monthly customer charge of $133.19/meter/month. We ignore this charge in our analysis.
- Energy charges per kWhr consumed that vary by season. For the summer season, June 1 to October 1, energy charges are $0.099 /kWhr. For the winter season, October 1 to June 1, energy charges are $0.080 /kWhr.
- Demand charges consisting of time-related demand and facilities-related demand charges.
    - The time-related demand charge is applied only during SCE's summer season from June 1 to October 1. It is a per-kW charge applied to the greatest amount of registered demand in each summer season billing period. A time related demand charge of $19.26 is levied per kW per month during 4 months in summer.
    - The facilities-related demand charge is also billed on a per-kW basis, yet it is in effect in each billing period throughout the year. It is applied to the greatest amount of registered demand in each billing period. A facility-related demand charge of $12.25 is levied per kW per month throughout the year.

The annual electric energy costs for lighting are computed by applying the SCE's electric energy charges for summer and winter seasons to baseline and post-retrofit energy consumption during summer and winter months, respectively. Further energy cost savings are attained due to reduction in peak demand, which is estimated based-on peak LPD reduction due to new system. Annual demand charges due to lighting are computed based on SCE's time related demand charges (for summer months) and facility related demand charges (throughout the year) to peak baseline and peak post-retrofit demands.

To estimate HVAC energy cost savings due to lighting upgrades we use the simulations results. Simulation results provide monthly heating and cooling loads for baseline and post-retrofit system configurations. We converted the cooling load into the electric energy consumed for cooling by dividing the cooling load with typical coefficient of performance (COP) for HVAC system. In Building 279, the heating system is electric so the same process is applied to convert heating load into electric energy consumed for heating. On the other hand, in the building models representing Buildings 602 and 279, the heating systems are gas based. For those buildings, the heating load is converted into natural gas consumption.

The annual electric energy costs for HVAC are determined by applying the SCE's electric energy charges for summer and winter seasons to baseline and post-retrofit electric energy consumption for HVAC during summer and winter months, respectively. The commercial price of natural gas for the state of California was sourced from U.S. Energy Information Administration which was $8.27 /mil cubic feet (MCF) in 2011.

Simulation results also provide the monthly peak heating (where applicable) and cooling loads that are converted into peak electricity demands by dividing the load with COP. Annual demand charges due to HVAC are computed by applying SCE's time related demand charges (for summer months) and facility related demand charges (throughout the year) to peak baseline and peak post-retrofit demands. In buildings where the heating systems are gas based, the demand charges do not apply. Aggregate annual energy costs are sum of electric energy charges (for lighting and HVAC), the demand charges (for lighting and HVAC) and natural gas costs.

7.2.3 Estimated Maintenance Cost Savings

The Hybrid ILDC and OccuSwitch systems have battery powered sensors. Because the batteries in the sensors will need replacements, the replacement costs have to be accounted in the life cycle cost calculations. Battery replacement costs are estimated based on lifetime of the battery (10 years), labor cost for replacement ($3.0 per battery for group replacement), material cost of the battery ($6.0 each), and battery deployment density (1 battery per 94 ft^2).

7.3 COST DRIVERS

The sophisticated systems (e.g., Hybrid ILDC and Dynalite) are more cost-effective in large installations for the following reasons. The cost of special equipment (e.g., central server) and software (e.g., database software and energy management software) get amortized over a large area. Similarly, design, installation, commissioning, supervision, inspection and overhead costs are apportioned over a larger floor space. Due to these economies of scale, the total investment per ft^2 reduces as coverage area increases.

The cost of installation, commissioning, supervision and inspection are sensitive to the local labor rate at the target site. These costs will also vary depending on whether unionized or non-unionized labor is used. Some DoD sites may have a limited pool of electrical contractors that are authorized to perform work at these sites, which could lead to higher costs.

The cost of electric energy significantly varies regionally. Energy costs play a significant role in payback time and savings to investment ratio computation. Higher energy costs lead to shorter payback time and vice versa. Typically, utilities offer many different rate structures. Utility rates also vary based on TOU (e.g., on-peak, mid-peak and off-peak conditions) and seasonally (summer schedule versus winter schedule). These factors influence return-on-investment and have to be analyzed on a case by case basis.

The utility rebates vary based on the type of control system. Some utilities provide rebates based on the quantity of control equipment, such as occupancy sensors and photo-sensors. Other utilities offer rebates based on the reduction in LPD.

Several factors influence energy savings potential of a lighting control system, such as building type, orientation, window to wall ratio, daylight availability, surrounding environment, daylight penetration, climate conditions, usage pattern, occupancy profile, type and efficiency of light sources, layout of lighting equipment. The Hybrid ILDC system not only saves lighting energy but also HVAC energy by regulating the admission of solar heat gain. The impact of integrated lighting and shading control system on HVAC energy consumption depends upon window-to-wall ratio, orientation of windows, climate conditions, solar irradiance patterns, type of HVAC system, reflectivity of blinds, location of blinds (external v/s internal) and control strategies implemented. In general, the HVAC cost savings due lighting controls are higher in warmer climates where cooling energy dominates.

7.4 COST ANALYSIS AND COMPARISON

The cost analysis was performed using the Building Life-Cycle Cost Program (BLCC5). To illustrate how the size of the installation impacts the cost benefit trade-offs for each technology, the three different deployment categories are defined based on the floor area covered per deployment. A small deployment is defined as a deployment with total floor area of less than or equal to 50,000 ft^2. A medium deployment is defined as a deployment with coverage area between 50,000 and 200,000 ft^2. A large deployment is defined as a deployment with coverage area more than 200,000 ft^2.

Based on the coverage area, the three systems deployed at Ft. Irwin fall under the category of small deployment. To derive costs for medium and large deployments, the results from Ft. Irwin are scaled based on the best engineering judgment and in-house data from other commercial projects.

The cost-benefit tradeoffs of a given technology are also influenced by several other factors such as the cost of energy, specific characteristics of the building, climate conditions, usage patterns and occupancy profile. To account for these variations, three implementation scenarios are defined.

The Ft. Irwin deployment was considered as a typical implementation scenario. A conservative implementation scenario was defined by scaling down the energy charges, demand charges and energy savings by factors indicated in Table 12. The conservative scenario captures unfavorable settings where energy costs and savings are significantly lower than Ft. Irwin scenario. On the other hand, an aggressive scenario represents the situation where energy costs and savings are higher than Ft. Irwin scenario.

Table 12. Energy and demand cost and savings assumptions for three implementation scenarios.

	Conservative	Typical (Ft. Irwin)	Aggressive
Electric energy charges	75%	100%	125%
Demand charges	75%	100%	125%
Lighting energy savings	80%	100%	120%
Lighting demand savings	90%	100%	110%
HVAC energy savings	80%	100%	120%
HVAC demand savings	90%	100%	110%

The economic benefits of retrofitting the existing lighting systems with the Hybrid ILDC, OccuSwitch, and Dynalite, respectively, are summarized in Tables 13, 14, and 15. The results are presented for three deployment categories for three scenarios defined in Table 12. The results in the row typical and in the column small deployment captures the cost-effectiveness of the system in Ft. Irwin. These tables show the wide spectrum of outcomes that are expected in commercial deployments.

Typically, with networked lighting controls solutions such as Dynalite and Hybrid ILDC, the central control server and associated software are costly elements that weigh heavily in smaller size deployments. Consequently, it can be seen in Tables 13, 14, and 15 that cost objectives (i.e., payback period < 7 years and SIR>2) are more readily met for medium and large size deployments and with aggressive energy and demand savings for smaller size deployments.

Each system is unique and suitable for specific building types. For example, it can be seen that the OccuSwitch system, due to its room or zone based control architecture, is more cost-effective for smaller size deployments compared to the others. Furthermore, for all the technologies demonstrated, the cost per unit area is expected to decrease as system deployments increase or as the systems get more mature. In the initial deployment phase costs are conservative or high and as they become more mature the cost can be more aggressive as shown in Tables 13, 14 and 15. Overall, it can be stated that for medium and large deployments, that as technologies gain maturity cost objectives will be met.

Table 13. Cost-effectiveness for Hybrid ILDC for three deployment and three implementation scenarios.

	Small Deployment		Medium Deployment		Large Deployment	
	Simple Payback Time (years)	SIR Over a 20 Year Period	Simple Payback Time (years)	SIR Over 20 a Year Period	Simple Payback Time (years)	SIR Over a 20 Year Period
Net Investment $/ft^2	5.64		3.51		2.79	
Conservative	9.85	1.00	6.13	1.80	4.87	2.20
Typical	6.25	1.60	3.89	2.80	3.09	3.40
Aggressive	4.33	2.40	2.69	4.00	2.14	5.00

Table 14. Cost-effectiveness for OccuSwitch for three deployment and three implementation scenarios.

	Small Deployment		Medium Deployment		Large Deployment	
	Simple Payback Time (years)	SIR over a 20 Year Period	Simple Payback Time (years)	SIR Over a 20 Year Period	Simple Payback Time (years)	SIR Over a 20 Year Period
Net Investment $/ft^2	3.40		2.25		1.44	
Conservative	8.52	1.20	5.65	1.80	3.61	2.80
Typical	5.37	1.80	3.56	2.80	2.28	4.40
Aggressive	3.71	2.60	2.46	4.00	1.57	6.20

Table 15. Cost-effectiveness for Dynalite for three deployment and three implementation scenarios.

	Small Deployment		Medium Deployment		Large Deployment	
	Simple Payback Time (years)	SIR Over a 20 Year Period	Simple Payback Time (years)	SIR Over a 20 year Period	Simple Payback Time (years)	SIR Over a 20 year Period
Net Investment $/ft^2$	4.54		3.39		2.25	
Conservative	13.55	0.80	10.12	1.00	6.70	1.40
Typical	8.67	1.20	6.47	1.60	4.29	2.40
Aggressive	6.05	1.60	4.51	2.20	2.99	3.40

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8.0 IMPLEMENTATION ISSUES

Lessons learned and issues encountered during these demonstrations are summarized in this section to aid in the future implementation of the technologies.

8.1 BUY-IN FROM STAKEHOLDERS

Securing the support of all the stakeholders especially from the DPW staff is essential for timely execution of the demonstration project. Presenting the objectives of the project and how they relate to DoD's energy security goals to senior leaders (e.g., Garrison Commander, Director of DPW, etc.) can help. Consulting information assurance manager and privacy officer during the planning phase can help mitigate any issues related to security and privacy.

8.2 ADDRESSING DPW CONCERNS

Articulating the goals of the project and how they align with the mission of DPW is important to get them excited. Defining the scope of work and roles of DPW staff is essential to manage the expectations. A point of contact for communications and approvals should be established to streamline the execution. Potential concerns such as reimbursement for the time spent by DPW staff and warranty of installed systems should be discussed.

8.3 ESTABLISHING THE CHANNEL FOR COMMUNICATION

A clear line of communication should be established with the base to communicate any issues, concerns, occupant complaints, or system faults back to project team in a timely fashion. A formal role of coordinator and reimbursement for coordinator's services should be discussed with concerned parties at the base. Note that the process for gathering user feedback is dependent entirely on the key contact at the installation site who alone can administer the process of handing out questionnaire and ensuring response, for reasons of anonymity and thoroughness. If required, the host site should also be willing to provide access to the building during off hours, nights and weekends. Electrical contractors hired for installation and commissioning should be able to gain access to the facilities. On-site support may be needed to receive and store equipment, supplies, and spares.

8.4 ADDRESSING REGULATORY ISSUES

Advanced planning to comply with regulatory requirements will help avoid any delays due to regulatory approvals. Requirements for DoD Information Assurance Certification and Accreditation Process (DIACAP) should be investigated early on. Certification requirements need to be clarified with the base so that valuable benefits of energy savings measures can be realized efficiently and effectively. If applicable, the DIACP approvals or waivers should be secured. Similarly, compliance to privacy policies should be ensured.

8.5 OVERCOMING BARRIERS TO ADOPTION

Energy efficiency is the key motivator for adopting advanced lighting controls. Other factors such as user satisfaction, occupant comfort, and productivity are important, however, not well recognized. More awareness about these factors among decision makers is needed.

DPW and other organizations responsible for maintaining the lighting systems are concerned about staff training and resources needed to maintain such advanced control systems. This sometimes dampens the enthusiasm for advanced control systems. This needs to be addressed broadly in DoD to benefit from the significant savings in cost and energy. Control systems with remote monitoring and automated fault detection, diagnosis and recovery features can address some of these concerns. Demonstration projects, such as this one, prove reliability and maintainability of advanced controls can help mitigate those concerns and accelerate the adoption. Maintenance contracts can be included in the procurement processes to ease the burden on local maintenance staff. Wireless controls are sometimes perceived as unreliable. In this project, no issues related to reliability of wireless controls were observed. More demonstrations of wireless controls in DoD settings can help overcome the perception and boost the credibility of wireless controls.

8.6 PROCUREMENT

Philips Lighting is one of the largest manufacturers of commercial lighting products in the U.S; and its control unit provides a complete line of commercial lighting control products. Hybrid ILDC system is a research prototype. Commercialization prospects of the system solution are being evaluated based on market research and performance results from in-house trials. Dynalite and OccuSwitch systems are commercially available now.

The Dynalite system is optimized for new constructions or deep retrofit where the incremental cost of wiring is minimal since it can be done during and together with the wiring of the rest of buildings. However, as shown in this demonstration project, the system can be effectively implemented in building with drop ceilings as well.

The OccuSwitch and the Hybrid ILDC system employing wireless radio frequency (RF) communication links are meant to be flexible and cost-effective for light retrofit in addition to new constructions and deep retrofit. The OccuSwitch system, with its modular room based or area based control, is suitable for small buildings where full networking is not required. The Hybrid ILDC as well as the Dynalite systems are most appropriate in large buildings where centralized monitoring and controls create value by allowing features such as demand response or peak load control.

Philips already possesses a broad distributor network that sells to both commercial and governmental entities including DoD. Philips offers its products as systems and components, and sells them primarily to original equipment manufacturers (OEMS), distributors and system integrators/value-added resellers (VAR) that provide turnkey installations to end users, including DoD bases. Philips has worked with many DoD installations to deploy commercial advanced lighting technologies. Since this project was initiated, the Dynalite has been installed at several sites in U.S. including some in DoD (e.g., Ft. Bliss). In support of its commercially released products, Philips provides technical specifications, data sheets, installation guides, quick-setup instructions, web casts, seminars and workshops. Also provided for commercial products are training (for installers, distributors and end users), commissioning, warranty, technical support, diagnostics, field upgrades, continuing education and new technology updates.

9.0 REFERENCES

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APPENDIX A

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